



Freezing Rain as an In-Flight Icing Hazard

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Note that at the time of research, the NASA Lewis Research Center's name had been changed to the NASA John H. Glenn Research Center at Lewis Field. Both names appear in this report.

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1. INTRODUCTION

It is well known that exposure to supercooled large drops (SLD – subfreezing water droplets with diameters greater than ~50 microns) can pose a significant threat to the safety of some aircraft. Although, by definition, SLD includes both freezing drizzle (FZDZ) and freezing rain (FZRA), much of the SLD research and development of operational SLD forecast tools has focused on FZDZ and ignored FZRA, regarding it as less of a hazard to aviation (e.g. McCann 1997). This mindset is primarily based on a few published FZRA encounters by one research aircraft where the resulting ice accretion was rather smooth, conformed to the airfoil and did not appear to cause a significant degradation in aircraft performance (Ashenden and Marwitz, 1997).

During the winters of 1997 and 1998, the NASA-Lewis Research Center Twin Otter made several flights into FZRA. Along with the collection of standard meteorological state-parameter and microphysical probe data, NASA engineers and pilots obtained detailed records of the ice accretions and performed maneuvers with the iced aircraft to assess performance degradation. On 4 February 1998 (980204), the NASA Twin Otter experienced a prolonged exposure to “classical” FZRA that caused a very different ice formation than that presented by Ashenden and Marwitz, and resulted in a substantial performance penalty.

Classical freezing rain develops when snow falls into a layer of above-freezing air (“warm nose”), melts to form rain, then subsequently falls into a sub-freezing layer of air to become supercooled (freezing) rain. In this paper, the meteorological setup for the 980204 FZRA event will be presented, including the synoptic-scale weather pattern, horizontal and vertical extent, temperature, and microphysical characteristics associated with it. The ice that accreted on the aircraft will be described, including its shape, location, and the resulting performance effects on the aircraft. Finally, the 980204 case will be placed in the context of climatological data on FZRA to assess its relevance.

2. THE NASA SLD FIELD PROJECT

NASA-Lewis has flown research aircraft into icing conditions for more than 15 years, focusing on the effects of icing on aerodynamic performance (Ranaudo

et al., 1986), and the ability to simulate ice formation on wings both in an icing tunnel (Miller et al., 1996), and in computer simulations (Wright and Potapczuk, 1996). Following the 31 October 1994 crash of an ATR-72 at Roselawn, Indiana, the NTSB identified SLD as a contributing factor in that accident. The FAA identified several turboprop commuter aircraft as potentially susceptible to these conditions, and is currently determining the potential need to expand the current icing certification envelope to include SLD. However, little research aircraft data exists that documents the range of temperatures, liquid water contents (LWC) and drop size distributions that comprise SLD conditions.

NASA-Lewis responded to this need by developing a joint research project with NCAR, AES (Atmospheric Environment Services – Canada) and the FAA that focuses on finding these conditions, sampling them and documenting their effects on aircraft performance. For this ongoing project, NASA provides a research aircraft, pilots with extensive flight experience in icing conditions (including SLD), and research and support staff to analyze the data, as well as maintain the instrumentation and the aircraft. AES has provided some of the instrumentation and expertise on its proper use and maintenance. NCAR provides daily icing/SLD forecasts, as well as in-flight guidance to NASA researchers via satellite telephone.

2.1 Research aircraft and instrumentation

The NASA-Lewis icing research aircraft is a modified DeHavilland DHC-6 Twin Otter. This twin turboprop aircraft is commonly used for local and regional commuter flights around the world. Ice protection is provided by pneumatic boots at the leading edges of the wing and tail, as well as along the vertical stabilizer and struts.

To properly document SLD conditions, the Twin Otter was equipped with a Forward Scattering Spectrometer Probe (FSSP; 2-47 microns), an Optical Array Probe (OAP) 1-D 260-X (7-625 microns), and an OAP 2-D Grey probe (7.6-968 microns). Overlap was maintained through much of the size range for redundancy and error checking. LWC measurements were provided by a King probe and Nevzorov LWC and total water content (TWC) probes. A Rosemount ice detector was used to document ice accretion rates. A

video camera was mounted in a pod above the fuselage, and provided a continuous means for monitoring and documenting ice accretion on the upper right wing surface (Miller et al. 1998).

Aircraft performance characteristics, such as lift and drag were derived from continuous measurements of aircraft accelerations, angular positions, mass, engine torque and propeller RPM. Level flight acceleration and deceleration maneuvers were used to derive the range of lift and drag coefficients by determining the maximum level speed and minimum speed before stall.

2.2 Other meteorological datasets

All other meteorological datasets used for this field project are derived from standard National Weather Service (NWS) instruments, including NEXRAD radars, the GOES-8 satellite, balloon-borne soundings, both manual and automated (e.g. ASOS) surface observations and voiced pilot reports (PIREPs) of icing and other in-flight conditions. These datasets are used both for forecasting and in-flight guidance, as well as post-analysis.

3. THE 4 FEB 1998 FREEZING RAIN CASE

In this section, a freezing rain event sampled by the NASA Twin Otter will be discussed, including the meteorological setup and cause of the event, the approach used to sample it, the exposure to freezing rain and resulting ice that formed, as well as an evaluation of the aircraft performance.

3.1 Setup for the freezing rain event

At 1200 (all times UTC) on 980204, a strong, closed low was in place over Georgia at 700 and 850mb (Fig. 1). To the northeast of the low, deep, saturated conditions and strong warm advection (WAA) were prevalent across the Appalachians, from Georgia to Pennsylvania (PA), and as far west as Ohio (OH) and Indiana. GOES-8 infrared imagery from 1545 UTC (not shown) indicate cloud top temperatures colder than -40°C across OH, PA and nearly all of West Virginia (WV), while the regional radar mosaic for 1600 UTC shows widespread precipitation across this area (Fig. 2). Although strong WAA was occurring at 850mb over WV at 1200, rather strong, cold advection preceded it, bringing cool, dry air down the western side of the Appalachians at 980204/0000 (not shown). This cold air remained in place at low levels across WV, OH and western PA well into 980205.

The 980204/1200 Pittsburgh sounding (Fig. 3) clearly indicates a sharp transition between the preexisting, cold air at low levels and the intrusion of warm air above 1km (all heights MSL). The wind direction changed from northeasterly below to easterly above this strong transition zone. Although temperatures were still subfreezing at all levels in the PIT sounding at 1200, the strong warm advection soon caused temperatures to exceed 0°C above 1 km. This classical freezing rain structure was common along the western side of the Appalachians (across 7 states) and persisted for roughly two days.

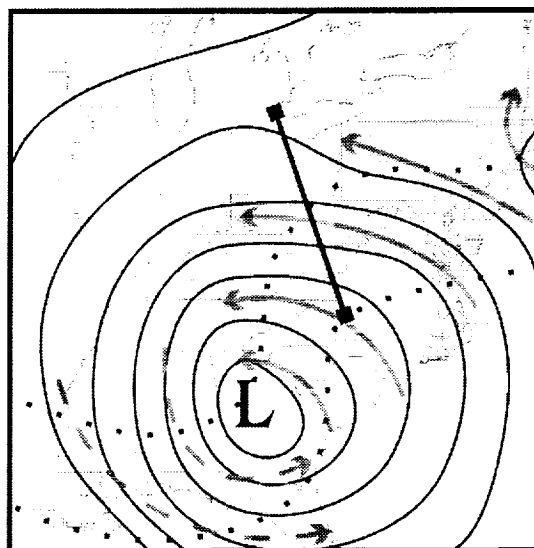


Figure 1. 700mb chart for 980204/1200. Solid lines are contours of height every 4 decameters, dotted lines are contours of temperature every 5°C , solid and dashed arrows indicate warm and cold advection, respectively. Shaded area indicates locations with dew point depression $< 5^{\circ}\text{C}$. Heavy black line with box-ends indicates the location of the cross section in Figure 4.

3.2 Research aircraft data – Flight 1

A total of three research flights were made on 980204, the second of which is of greatest interest here. In the first flight, the Twin Otter departed Cleveland at 1441 and ascended to 4900m. A FZRA temperature structure was in place there, but Cleveland was to the northwest of the precipitation shield at that time. The aircraft descended and flew southward at $\sim 3600\text{m}$, in search of some possible pockets of icing at upper levels on the northern fringe of the storm, to the north of the significant precipitation. The upper cloud mostly consisted of ice crystals and had very low LWC, so the aircraft descended to 915m (3000') just N of the precipitation area and headed toward Parkersburg WV (PKB) in an effort to sample the FZRA there.

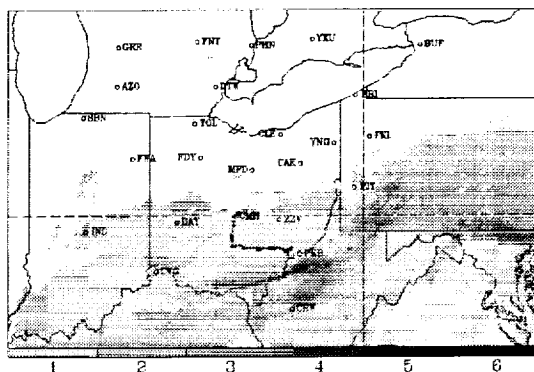


Figure 2. Regional mosaic of radar reflectivity for 980204/1600. VIP level (gray shading) and Twin Otter tracks for 1530-1630 (black '+' signs) are indicated.

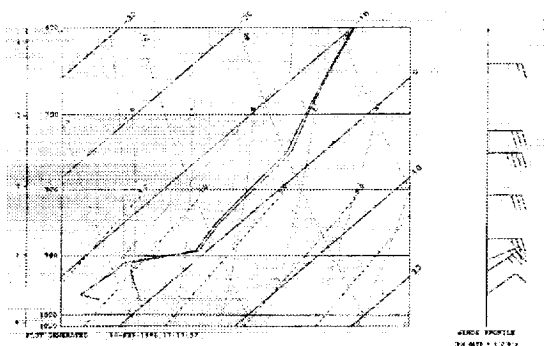


Figure 3. Skew-T Log-P diagram for Pittsburgh PA at 980204/1200.

Moderate-to-severe mixed icing was reported by a Cessna Citation II in the FZRA layer near Huntington, WV.

During descent, the aircraft crossed the top and base of the “warm nose” (layer of above freezing air) at 2100 and 1200m, respectively. Very light rain was observed in this layer. The Twin Otter entered the sub-freezing layer near the OH/WV border, but was still to the NW of the significant precipitation. Very light FZRA, mixed with cloud droplets and $T_s = -3^\circ\text{C}$ were encountered below 1200m. Maximum droplet sizes exceeded 1mm. According to the Rosemount ice detector, ice began to accumulate slowly until the aircraft entered the significant precipitation and LWC ($\sim 0.1 \text{ gm}^{-3}$), when it began to accumulate more rapidly. Due to fuel constraints, the aircraft did not have time to loiter in the FZRA layer and had to land at PKB at ~ 1655 to refuel. Clear ice pellets and some snow were observed upon landing. This ~ 20 minute exposure to FZRA resulted in the accretion of significant ice on the airframe, including a $\sim 1/2$ ” tall ridge at the end of the active part of the wing deicing boots.

3.3 Research aircraft data – Flight 2

The Twin Otter took off from PKB at 1818 in moderate ice pellets, and flew toward the southeast, ascending to 1570m, and crossing the base of the “warm nose” near 1200m. Moderate rain, temperatures up to $+3^\circ\text{C}$ and strong easterly winds were observed near 1500m. The clean (but wet) aircraft descended to 915m at 1833, and encountered a very strong vertical T gradient at the base of the warm nose. The temperature fell from $+2.3^\circ\text{C}$ at 1400m to -2.3°C at 1190m and remained at or below -2°C down to 915m. The plane remained at or near an altitude of 915m until 1959.

At 1833, the Twin Otter turned to the NW to do a horizontal transect between Zanesville, OH (ZZV) and ~ 50 km southeast of PKB. Static temperatures (T_s) remained fairly steady near -2°C (total temperature (T_t) was roughly -1°C), and LWC was typically between 0.05 and 0.2 gm^{-3} in FZRA as the plane flew toward PKB just above the height of cloud base over the next ~ 10 minutes. Again, maximum drop sizes exceeded 1mm, and reflectivity values from the Charleston, WV radar were between 25 and 45 dBZ in the FZRA layer. Glaze ice began accreting immediately both on and well

aft of the deicing boots during this period (A). Icing was quite noticeable on the windshield wipers and on the cockpit side windows within three minutes.

Cloud bases were slightly higher to the NW of PKB. Between 1843 and 1915 (period B), the Twin Otter flew a transect to and from ZZV in FZRA within or just below cloud base. LWC values were mostly between 0 and 0.05 gm^{-3} during this period, and temperatures gradually increased to near -1°C (T_t near 0°C).

Glaze ice continued to accrete and a $1/4$ ” ridge was evident at the end of the active portion of the deicing boot by 1847 (exposure time ~ 14 minutes). At that point, the deicing equipment was first activated and set on “auto-slow” (boots cycle every 170 seconds), then increased to “auto-fast” (boots cycle every 60 seconds) at 1857. With the boots operating, a clear ice accretion remained on and aft of the boots. During boot inflation, this clear/invisible accretion became white/opaque, then returned to clear upon boot deflation. A ridge also became noticeable on the tail by 1900, and a second ridge became evident on the wing roughly 3-5% chord aft of the deicing boot by 1902. This second ridge was very difficult to see, except for where it met a wing fence that was painted black. The T_t was so close to 0°C that pieces of the leading ridge on the wing would break off, making it discontinuous. During this period, “nodules” of ice began to grow on much of the fuselage and the undersides of the wings, well aft of the deicing boots. Note that the initial ridges, glaze accretions and ice nodules all built within ~ 15 minutes in FZRA conditions with low LWC.

The Twin Otter flew between 0 and 55 km SE of PKB between 1915 and 1959 (period C). In this area, the cloud bases were slightly below 915m, and the aircraft encountered FZRA mixed with small droplets (LWC mostly between 0.1 and 0.25 gm^{-3}) and cooler temperatures ($-2.8 < T_s < -2^\circ\text{C}$; $-1.4 < T_t < -0.5^\circ\text{C}$). During this period, the Rosemount ice detector cycled rapidly, a glaze accretion continued to form on the active portion of the boots, nodules continued to grow on the fuselage and undersides of the wings, and both wing ridges aft of the active portion of the boots grew to reach heights of $1/2$ to 1”. Ice covered both the upper and lower surfaces of the wing to 30-40% chord, and small portions of the ridge at the end of the active boot occasionally blew off.

3.4 Aircraft performance evaluations – Flight 2

Following the ~ 90 minute exposure to icing conditions, the aircraft climbed to 1310m at 2002 UTC. The aircraft was not climbing well, even at full power. A small break in the cloud deck was found at 1280m, allowing for further photographic documentation of the ice shapes. T_s was -2°C and FZRA conditions persisted at this altitude. Beginning at 2005, the Twin Otter did a total of three performance sweeps, finding the maximum speed to be ~ 115 knots and buffet speed to be ~ 90 knots. Comparing these values to clean aircraft speeds of 150 knots (max) and 68 knots (buffet) for this altitude indicates that the flight envelope decreased by $\sim 70\%$. Detailed analysis of lift and drag curves showed that the coefficients of drag increased by ~ 60 – 200%

(depending upon the angle of attack) and the maximum coefficient of lift was reduced by ~30%.

Granted, this is the result of 90 minutes of exposure to FZRA conditions. However, continuous aircraft performance indicate that most of the increase in drag occurred during 25 minutes of period C (1917-1942), when cloud droplets and FZRA were both encountered. Also, nearly all of the increase in engine torque pressure and thrust necessary to maintain a 915m altitude occurred during the same period. An increase in the drag coefficient was also evident during period A, a ~10 minute exposure to conditions similar to (and in the same area as) those found during period C. A performance sweep was not made at that time. Very little performance change was noted during period B, when the Twin Otter sampled along and just beneath cloud base, where FZRA, but relatively few cloud droplets and very little LWC were present.

It appears that nearly all of the change in the performance capabilities of the aircraft occurred during 35 minutes of the two exposures to FZRA mixed with cloud droplets. The development of the initial glaze accretions and ridge during the 10 minutes of FZRA and relatively low LWC encountered during period A are likely to have played a role by providing growth sites for the FZRA and cloud droplets that impacted the aircraft during period C.

3.5 Flight 3 - FZRA structure and longevity

The third flight on 980204 was designed to document the changes in the FZRA structure between PKB and CLE (Cleveland). This was done between 2200 and 2355 UTC, using a series of aircraft soundings made during takeoff at PKB, missed approaches at ZZV and CAK (Canton-Akron OH), and landing at CLE. Precipitation was heaviest at PKB and decreased gradually toward the north until reaching its northern fringe at CAK. Although a classical freezing rain temperature structure was present at all stations, rain was falling at PKB ($T > 0^{\circ}\text{C}$ at the surface), light snow was occurring at ZZV (ASOS observation - the aircraft observed light FZRA) and spotty, very light FZRA was found at CAK, while CLE was in overcast conditions.

Sounding data from 980204/2300 at Detroit, MI (DTX), Roanoke/Blacksburg VA (RNK) and Greensboro, NC (GSO) are combined with the aircraft soundings from 2200-2355 to create a SE-NW vertical cross section of the temperature structure present during the afternoon of 980204. Fig. 4 reveals that the temperature structure necessary for classical FZRA was present across essentially the entire cross-section, covering a distance of ~740km. The melting and potential FZRA layers were each about 1km thick and the $T < -2^{\circ}\text{C}$ layer was at least 0.5km thick across most of this distance, and was located almost entirely above cloud base. The FZRA conditions existed at altitudes as high as 1900m at RNK and 1370m at PKB, at common altitudes for aircraft to hold (3000-6000 feet) and suffer prolonged exposures, similar to those experienced by the Twin Otter.

The classical FZRA thermodynamic structure was evident in NWS soundings taken around the region

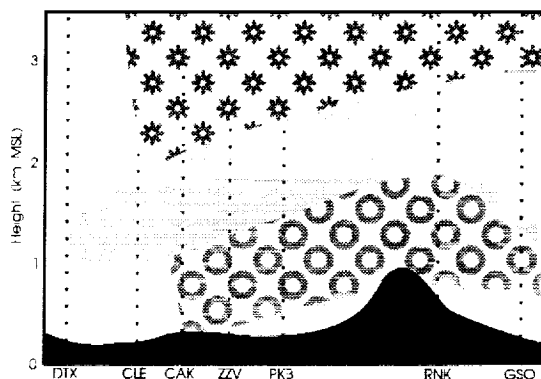


Figure 4. Vertical cross-section of weather conditions present at 980205/0000. Shading is as follows: below ground (black), $T > 0^{\circ}\text{C}$ (solid gray), freezing rain layer (gray circles), snow/ice crystal layer (gray stars). Black dotted lines indicate vertical data coverage at each site.

between 980204/1200 and 980205/1200, including over such major airports at Washington/Dulles and Pittsburgh. NASA sampled this same (though slightly shallower) FZRA layer over Columbus, OH at 980205/1600 and encountered similar conditions to those seen on 980204. Precipitation was falling in the form of FZRA or RA, mixed with ice pellets and snow at times, across much of the region for most of these two days. Thus, FZRA with $T < -2^{\circ}\text{C}$ was likely to have been present over this large area, through a significant depth, over a period of more than 24 hours.

4. FZRA - KEY ISSUES AND OTHER CASES

Overall, this case clearly shows that exposure to "classical" FZRA had a significant effect on the aerodynamic performance of the Twin Otter on this day. This information must be considered carefully and put into the context of other research flights into and climatological information on classical FZRA.

4.1 One drop size range versus the full spectrum

In this case, the initial ice ridges, glaze accretion and nodules all developed in FZRA with low LWC. Performance characteristics showed little change during periods when small droplets were not present. While the large droplets are likely to be critical to the formation of ice, and potentially hazardous shapes (e.g. ridges), on unprotected areas of the aircraft, the ice does not seem to grow rapidly in large drops *alone* (period B). However, when the full spectrum of drop sizes (including supercooled rain, drizzle and cloud droplets) impacted an aircraft upon which large droplets had caused initial accretions to form, the preexisting ice was able to grow rapidly (period C). Even the exposure of the clean aircraft to the full range of drop sizes allowed unusual ice shapes to form on unprotected surfaces (via the large drops), and to simultaneously grow at a rapid pace on the new collection surfaces (flight 1 and period A of flight 2). Jeck (1996) noted that the inclusion of small droplets can add to the ice accretion from FZRA.

The same issue may apply to freezing drizzle (FZDZ) accretions that result in ice ridges and droplet collection on unprotected surfaces. Data from other

FZRA and FZDZ cases sampled by NASA during 1997-98 seem to indicate that the inclusion of cloud droplets may be important to the effect that SLD has on aircraft performance. Further study is necessary to draw firm conclusions. When FZRA is occurring, FZDZ is part of the droplet spectrum that is present, and that the drizzle size ranges typically contain 10-25% of the liquid water content that is available for ice accretion (Jeck, 1996).

4.2 Temperature and boot use considerations

It is important to note that all of the ice accreted during the second flight occurred at temperatures warmer than -3°C ($T_i > -2^{\circ}\text{C}$), and that runback was not evident during this case. Thus, rather warm FZRA can cause significant icing to form on an aircraft wing. Even an aircraft flying at much faster speeds than the Twin Otter may accrete ice well beyond protected surfaces in FZRA. The presence of runback could worsen the situation by enhancing ice growth on collection sites further back on the wing.

Jeck (1996) noted that when the University of North Dakota Cessna Citation was exposed to FZRA, the fastest ice accretion appeared to occur at the coldest temperatures (-8°C in that case). A significant performance hit was noted, but the location of ice formations on the aircraft was not discussed. Further study is needed on the importance of temperature on ice formation in FZRA.

It is unclear whether or not the use of the boots may have affected the growth of ice ridges in this case, but on this day, the same ice shapes seemed to grow both when the boots were inactive (flight 1) and active (flight 2). During this flight, the boots appeared to be unable to remove the ice. However, the boots were not designed to handle FZRA conditions, where droplet sizes exceed those of the FAA icing certification envelope (FAA, 1974). No aircraft is certified for flight into FZRA conditions.

4.3 Climatology of FZRA layers

To assess how representative the conditions encountered on 980204 were, this case must be put into the context of FZRA cases, in general. Jeck (1996) studied balloon-borne soundings launched from sites across the United States when FZRA was occurring at the surface, and found that the average lowest temperature within the FZRA layer was typically between -4 and -9°C . Considering that these are the coldest temperatures measured within the FZRA layer, and the fact that the temperature is $>0^{\circ}\text{C}$ at some higher altitude, layers of FZRA with $T > -3^{\circ}\text{C}$ are rather common. Jeck also notes that the FZRA layers are typically 1 to 2 km (3000-6000') in depth, and can be nearly 4 km (12000') deep. Overall, the FZRA layer sampled on 980204 was fairly typical in terms of depth. Unfortunately, to the authors' knowledge, a climatology of cloud base height relative to supercooled layer height is not available. This may be a topic of future work.

5. CONCLUSIONS

This case study clearly demonstrates that exposure to classical FZRA can cause significant ice to accrete on the Twin Otter airframe, including ice ridges and nodules on unprotected surfaces. Such ice ridges were identified as a possible contributing factor in the crash of an ATR-72, killing all 68 people on board. The inclusion of a full range of drop sizes, including supercooled rain, drizzle and cloud droplets, seemed to enhance ice growth and cause the greatest rate of change in aircraft performance. Subsequent performance tests revealed a dramatic increase in aircraft drag, and decrease in lift that decreased the size of the Twin Otter's safe operating window.

Clearly, classical FZRA can pose a significant in-flight icing hazard, and should not be ignored when considering SLD issues. It is important to note that this is just one case, sampled by just one airplane. That same situation may have very differently affected other aircraft flying with different wing configurations at different speeds and air temperatures. Jeck (1998), using the NASA LEWICE ice accretion code showed that a Twin Otter wing geometry will typically accrete less ice than other commuter class airframes (e.g. ATR-72) and research aircraft (e.g. King Air). These comparisons were made for small-drop icing, however, and may not apply for large-drop icing.

The FZRA cases presented by Ashenden and Marwitz (1998) did not seem to result in a major performance penalty, while the UND case (Jeck 1996) and the Parkersburg case (presented here) were associated with substantial performance penalties. Similarly, NASA encounters with FZDZ have met with a variety of performance penalties, from essentially none to severe. Considering the variety of SLD scenarios that exist in the atmosphere, the possible combinations of droplet size, LWC, T , depth, coverage and longevity of these conditions, we must consider the FZRA and FZDZ cases in the literature as point values. Until we have a more complete sample of the spectrum of SLD conditions that exist, we should not discount or overstate the importance of any one portion thereof.

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13. ABSTRACT (Maximum 200 words) Exposure to supercooled large drops (SLD—subfreezing water droplets with diameters greater than ~50 microns) can pose a significant threat to the safety of some aircraft. Although SLD includes both freezing drizzle (FZDZ) and freezing rain (FZRA), much of the SLD research and development of operational SLD forecast tools has focused on FZDZ and ignored FZRA, regarding is as less of a hazard to aviation. This paper provides a counterpoint case study that demonstrates FZRA as a significant in-flight icing hazard. The case study is based on flight and meteorological data from a joint NASA/FAA/NCAR SLD icing research project collected on February 4, 1998. The NASA Twin Otter Icing Research Aircraft experienced a prolonged exposure to "classical" FZRA that formed extensive ice formations including ridges and nodules on the wing and tail, and resulted in a substantial performance penalty. Although the case study provides only a singular FZRA event with one aircraft type, it is clear that classical FZRA can pose a significant in-flight icing hazard, and should not be ignored when considering SLD issues.				
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